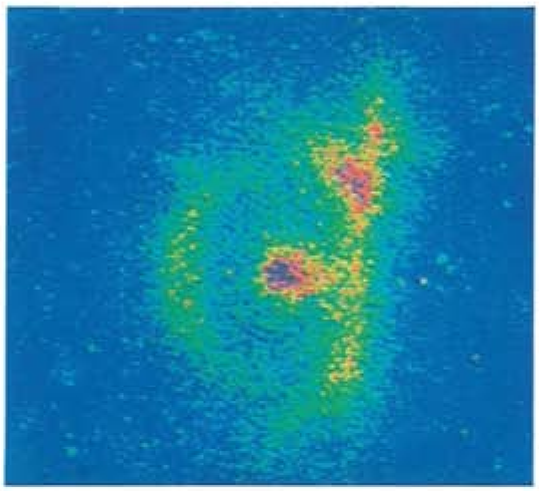
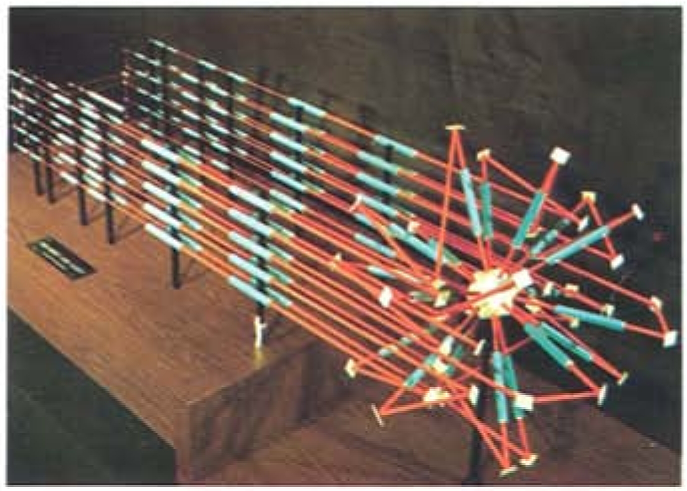
UCRL-52000-76-2

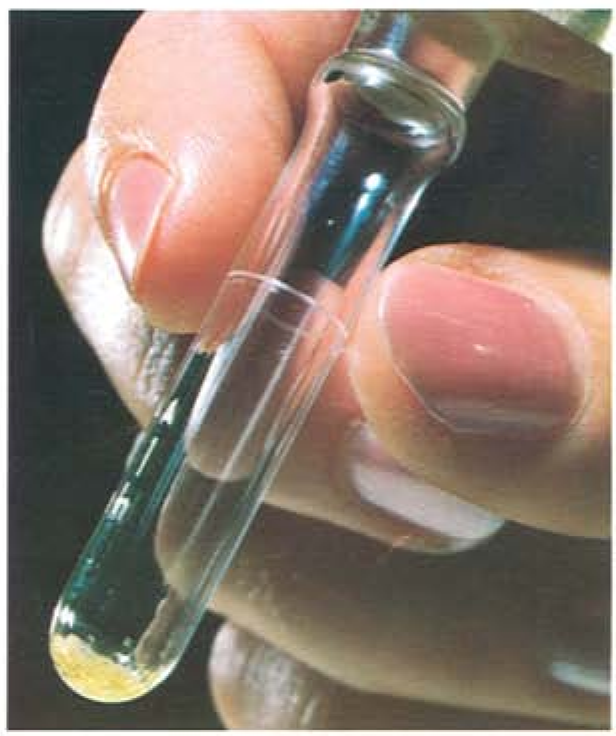
Energy and Technology Review

FEB. 1976

Prepared for U.S. Energy Research & Development Administration under Contract No. W-7405-Eng-48







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LLL LASER PROGRAM

Cyclops, a single-chain Nd:glass laser, produces a 1-TW subnanosecond pulse whose brightness exceeds 10^{18} W/cm^2·sr. This is state-of-the-art performance for solid-state laser technology. Three key factors have contributed to this achievement: disk amplifiers in the final power stage with 20-cm clear apertures, spatial filters for controlling small-scale self-focusing, and quadratic apertures for minimizing whole-beam distortion. Cyclops serves both as a prototype for future multiarmed laser systems and as a full-scale experimental amplifier facility for investigating beam-propagation phenomena and testing system components.

A number of laboratories throughout the world are actively developing pulsed high-power Nd:glass lasers to study laser fusion and laser-plasma interaction. LLL presently operates two neodymium laser systems – Cyclops and Janus – and is building two more – Argus and Shiva. As reported in the overview article, these solid-state systems are designed to supply the energy, power, and wavefront uniformity required to spherically implode nuclear fuel targets and achieve fusion through inertial confinement.

The requirements on the optical performance of fusion lasers are staggering. Targets as small as 100 μm in diameter must be uniformly irradiated with multiple beams each delivering between 100 and 1000 J of energy. This energy must be delivered in a single, time-tailored pulse whose peak power exceeds 1 TW. To achieve the requisite uniformity and brightness of illumination at this power level, we must thoroughly understand numerous linear and nonlinear propagation phenomena.

Cyclops is a single-chain prototype built as an experimental test bed for investigating beam propagation and evaluating laser components. We have tested all key components through D-size (30-cm aperture) disk amplifiers on Cyclops. Beam quality, servo-controlled alignment, and laser beam diagnostics will continue to be studied and developed at this facility. We are currently investigating two nonlinear propagation phenomena in particular: small-scale self-focusing and whole-beam distortion. They pose serious problems in terms of component damage and diminished ability to focus the beam.

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Cyclops Laser Chain

The Cyclops laser chain is shown schematically in Fig. 14. The dye-mode-locked Nd:YAG oscillator with its optically triggered spark-gap switchout produces a single 1.5-mJ, 100-ps pulse of 1.06-μm light. This pulse is amplified by two stages of rod preamplifiers and three stages of disk amplifiers. The basic staging after initial preamplification includes an iteration of multilayer dielectric-coated polarizers, pulsed Faraday rotators, and amplifiers. The rotator-polarizer combinations provide about 25 dB of backward attenuation for each 10 dB of gain in the forward direction. This ensures that laser components will not be damaged as a result of target reflections.

The rod preamplifiers range in clear aperture from 9.5 to 25 mm and deliver a nominal 0.2-J pulse to the first stage of disk amplifiers. After the 9.5-mm preamplifier we have placed a dye cell to absorb small precursors (prepulses) but transmit the main large pulse. A spatial filter and beam-shaping aperture follow the dye cell. The aperture, described in detail below, superimposes a prescribed intensity profile on the propagating beam.

The A, B, and C disk amplifiers have clear circular apertures of 36, 82, and 200 mm, respectively. The A and C amplifier stages consist of 12 elliptical disks, the B of 18; all disks are mounted at the Brewster angle. The A and B modules house six disks each; the C modules house three disks. The disks are pumped radially by 184 closely coupled linear flashlamps (12 to 32 lamps per module). The combined capacitive energy storage to fire these lamps is 1.6 MJ. Figure 15 shows the interior of a C module; the dimensions of each elliptical disk are 21 × 40 × 3 cm with a surface flatness of 1/8λ at 632.8 nm and a doping concentrate of 2 wt% Nd_2O_3. Like the chain's other disks, their edges have an absorptive glass coating to suppress parasitic oscillations and reduce fluorescence depumping.

A high-energy spatial filter is placed between the B and C amplifier stages. This filter consists of an *f*/10 lens-pinhole combination housed in an evacuated chamber. Chamber pressure is kept below 13 Pa to reduce the possibility of air or material breakdown at the 300-μm-diameter diamond pinhole. The filter retards beam filamentation, a propagation phenomenon discussed below.

After the spatial filter, a pair of rotatable cylindrical lenses correct linear astigmatism. This lens pair has a

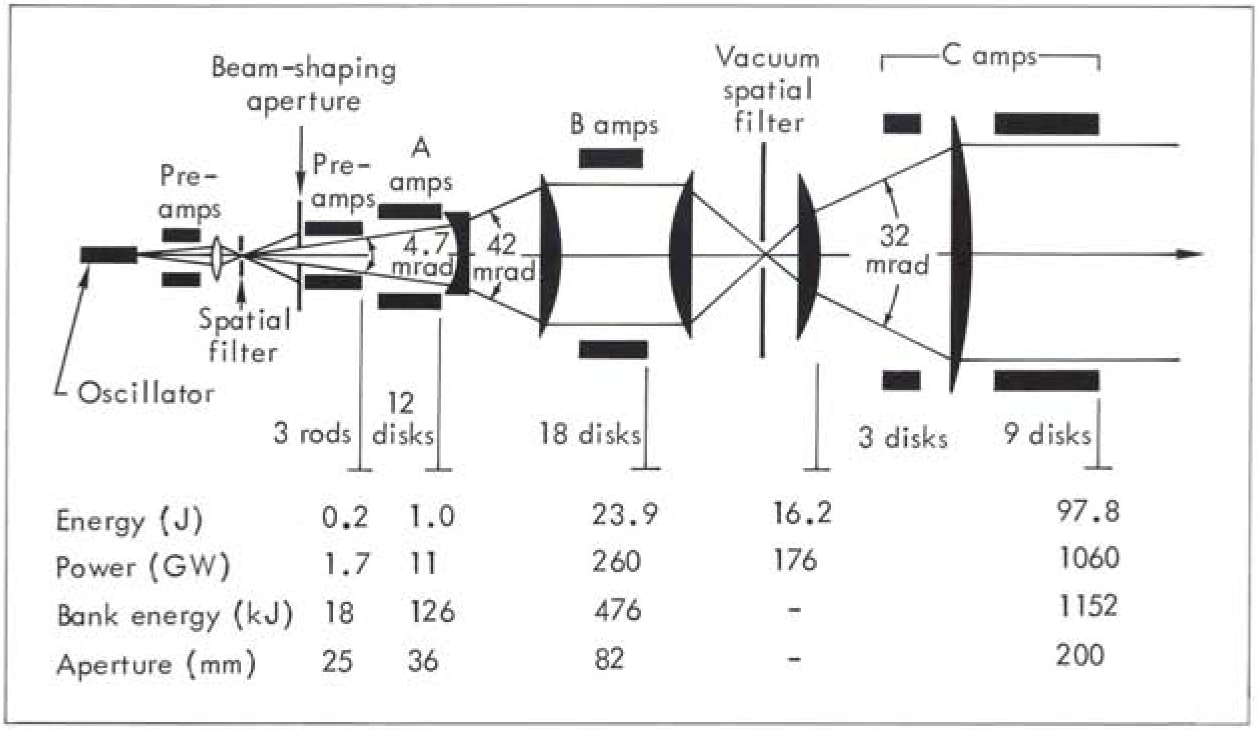

Fig. 14. Simplified schematic of the Cyclops laser chain showing representative values for power and energy at each stage.

range of about three waves and is adjusted by monitoring the far-field pattern of a continuous-wave beam that traverses the same path as that of the pulsed beam.

Figure 16 is a photograph of the Cyclops laser chain viewed from the final output stage.

Small-Scale Self-Focusing

Today, beam instability resulting from small-scale self-focusing is the single most limiting factor in achieving increased brightness from a Nd:glass laser. Self-focusing occurs when an intense optical beam passes through matter and the beam's high intensity increases the refractive index of the material. This interaction between beam and system components means that any small intensity irregularity in the beam induces a lens for itself. The induced lens focuses the irregularity still more, and the enhanced irregularity

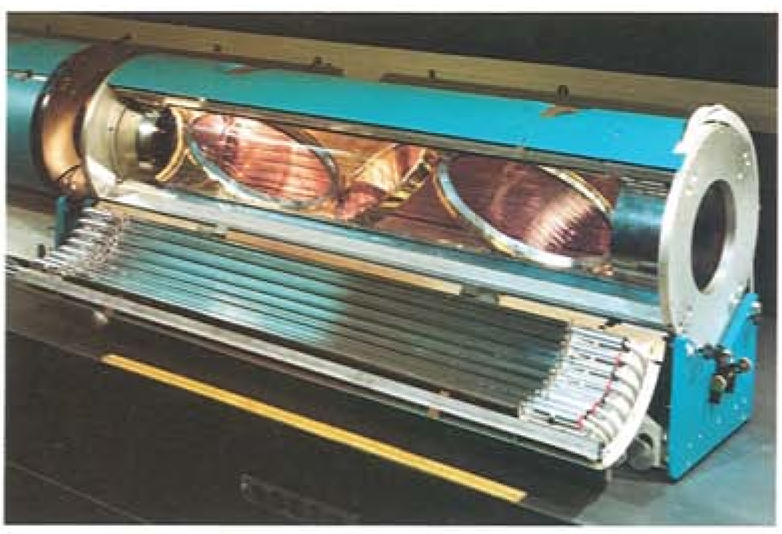

Fig. 15. Interior of a C-amplifier module with a clear aperture of 20 cm. When pumped with 280 kJ of bank energy, the module achieves a small-signal gain of 6.5%/cm, which corresponds to a net gain of 1.8.

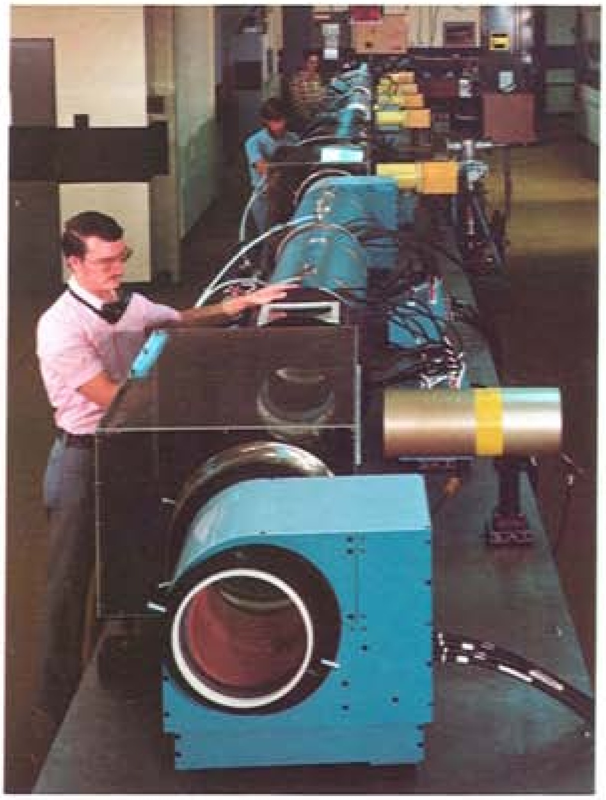

Fig. 16. Cyclops laser chain as viewed from the C-amplifier output stage.

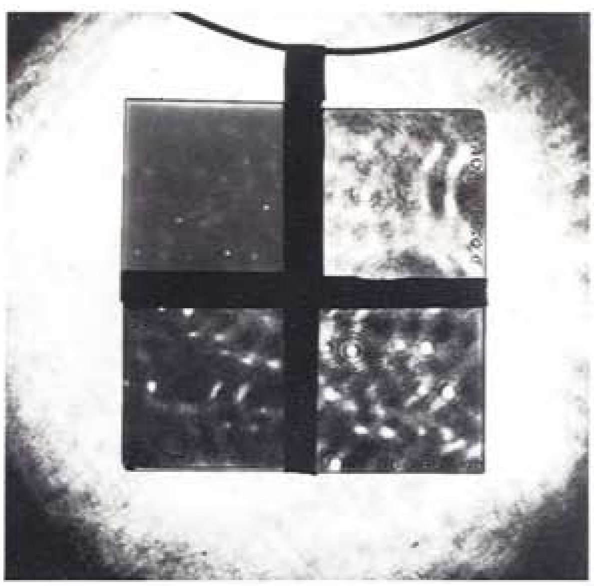

Fig. 17. Near-field photograph of the Cyclops beam at the output of the final C amplifier. For this shot the B-stage spatial filter was removed; beam energy was about 270 J and power about 1 TW. The four neutral density filters reveal the beam's filamentary structure (mottled patterns and bright spots of light).

in turn induces a stronger lens. Beam instability can grow exponentially in this manner.

Small-scale self-focusing produces beam filaments (hot spots) whose intensity can exceed the average several hundredfold. If allowed to progress too far, the beam-breakup process of self-focusing can damage system components, such as glass rods and disks, polarizers, Faraday rotators, and lenses; the focused beam is also seriously degraded. Beam breakup is manifest in deep, high-frequency modulations on the beam profile.

The consequences of uncontrolled small-scale beam breakup are revealed in a near-field photograph of the Cyclops beam taken at the output of the final C amplifier (Fig. 17). For this shot, the spatial filter between the B and C amplifier stages was not in place; beam energy was about 270 J and power about 1 TW. Four neutral density filters placed in front of the camera and near beam center reveal the beam's structure. Filamentation is clearly evident in the mottled patterns and bright spots of light. Intensity variations of 10:1 can be identified; even greater variations are expected to be present within the glass medium.

One remedy for small-scale self-focusing is the introduction of spatial filters to retard the rapid growth of beam filaments. The spatial filter – a combination of two lenses and a pinhole aperture – forces the exponentiation of small-scale structure to start over again, rather than allowing it to continue until it leads to large energy losses. A perfect filter would pass the background beam undistorted while stripping away the high-spatial-frequency ripples or modulations.

Figure 18 shows the dramatic effect that the Cyclops B-stage spatial filter has on a beam badly degraded by small-scale filamentation. The upper photograph and microdensitometer traces are of a beam that exhibits severe filamentation; the lower show the same beam as it looks after passing through the spatial filter. The high-frequency filamentary structure has been smoothed while the overall beam shape remains substantially the same. The successful development and use of spatial filters on Cyclops have, for the first time, provided us with a practical means of controlling small-scale self-focusing in high-power Nd:glass laser chains.

Whole-Beam Distortion

A second major beam-propagation problem that must be addressed in designing large Nd:glass laser

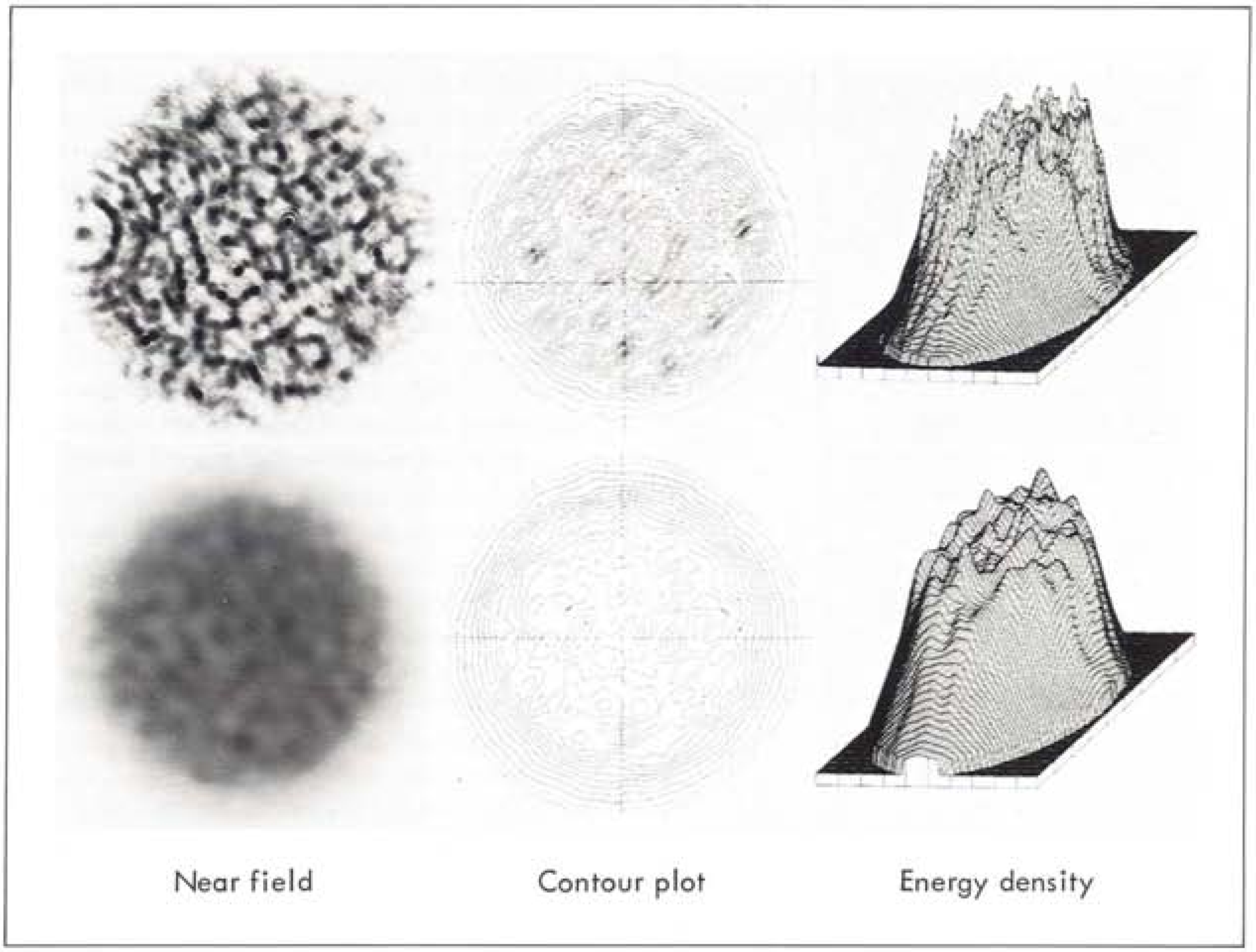

Fig. 18. Photographs and microdensitometer traces of a structured beam before (top) and after (bottom) transmission through the Cyclops B-stage spatial filter. The filter smooths the high-frequency filamentary structure but leaves the overall beam shape substantially unchanged.

chains is whole-beam self-focusing. This distortion causes phase shifts (aberrations) across the beam profile that seriously degrade our ability to focus the beam. Although these shifts are small (several waves), they can give rise to large intensity and phase variations in regions of the beam where small fusion targets are likely to be placed. Like small-scale self-focusing, whole-beam distortion results from the interaction of the intense beam with matter through the indices of refraction. The differences are largely ones of spatial scale and magnitude.

One remedy for whole-beam distortion is to shape the beam so that the intensity-induced aberrations are simplified and illumination nonuniformities are minimized. We have found that this shaping can be accomplished with a graded aperture having a parabolic transmission profile. Since the distortion is proportional to intensity, the shaped beam will experience a weak parabolic lensing; this yields a simple time-dependent motion of the focal plane, which can be dealt with.

The desired spatial profile for the beam represents a compromise between diffraction-ripple buildup and the amplifier filling factor. That is, we must choose the graded aperture such that near-field diffraction ripples, which can be amplified by self-focusing, are minimized and amplifier apertures are effectively filled by the beam for optimum power extraction. The advantage of the parabolic (or modified-quadratic) profile we are now using is best illustrated by comparison with previously used profiles, such as the super-Gaussian and Airy disk (see Fig. 19).

Figure 19a shows relative intensity profiles for the Airy disk, super-Gaussian, and quadratic aperture functions. The Airy disk does a poor job of filling, or covering, the aperture; the super-Gaussian and

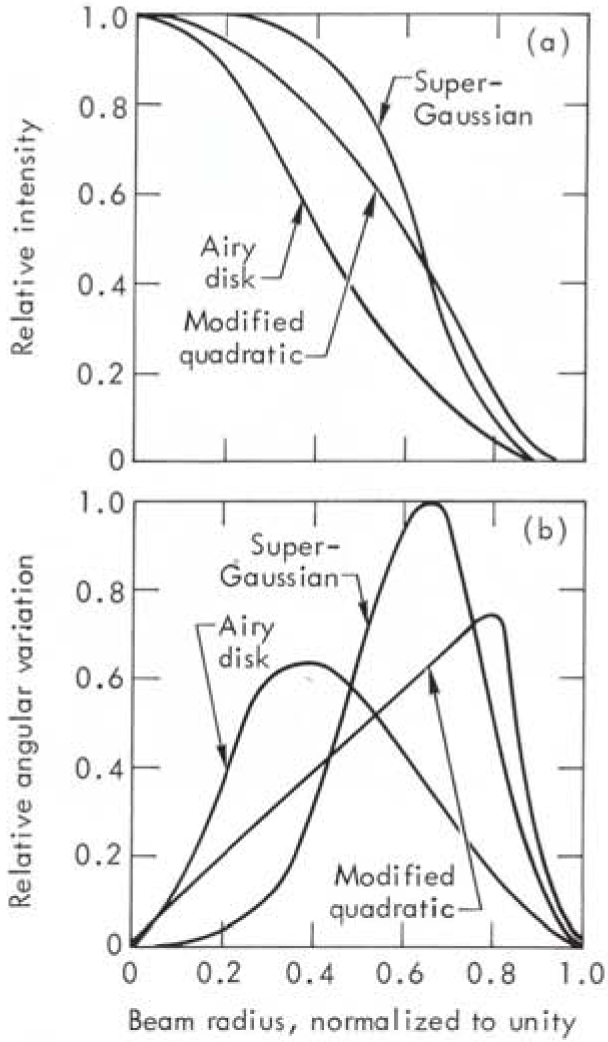

Fig. 19. Relative intensity profiles (a) and near-field angular variation of the rays (b) for the Airy-disk, super-Gaussian, and modified-quadratic beam shapes. Overall, the modified quadratic yields the best results.

quadratic do considerably better. For pellet illumination, however, we also need high brightness and spatial uniformity. This half of the compromise is illustrated in Fig. 19b, which gives the angular deviation of the beam rays with respect to the z-axis that would result from whole-beam distortion. Both the Airy disk and the super-Gaussian give rise to angular distributions that would be expected to yield complex intensity and phase distributions in the focal region. The modified quadratic, on the other hand, yields a simple linear variation over a substantial portion of the aperture; such linearity is characteristic of a thin lens. The rays associated with the quadratic profile, therefore, can be brought to a common focus, whereas the other beam shapes will yield a complex distribution of foci along the z-axis.

To examine these focusing properties in greater detail, we have developed a diffraction program called ZAX that can be applied to beams with quite arbitrary intensity profiles. When we use this program to compare the focal-volume intensity distributions resulting from beams with super-Gaussian and modified-quadratic aperture functions, we again find that the latter is superior for uniform target illumination. If we assume an absence of intensity-induced aberrations, both the super-Gaussian and quadratic beams propagate quite well into the far field. However, when we add 1.5 waves of whole-beam distortion, only the quadratic remains relatively undistorted by the aberrations.

Summary

Cyclops produces a 1-TW pulse whose brightness exceeds 10^{18} W/cm^2·sr. Such performance in the 0.1- to 1-ns regime from a single laser chain represents today's state of the art in high-power Nd:glass laser technology. We have achieved this performance through a combination of 20-cm-clear-aperture disk amplifiers in the final power stage, a spatial filter to lessen small-scale self-focusing, and quadratic apertures for minimizing whole-beam distortion. The expertise and technology developed on Cyclops have also enabled us to design and build much larger and more complex glass laser systems such as Argus and Shiva. We are continuing to use Cyclops as a laser test bed for component and laser-system development.

Key Words: Cyclops; laser beams – distortion; laser beams – focusing; laser beam – nonlinear effects; laser beams – propagation; laser pulses – nonlinear effects; laser pulses – propagation; laser pulses – self focusing effects; lasers – amplification; lasers – Lawrence Livermore Laboratory; lasers – self focusing effects; self focusing effects.